

PISTON TEMPERATURE
MEASUREMENT AND PISTON
DESIGN INVESTIGATION
ON A C. F. R. ENGINE

BY

N. O. WITTMANN
J. H. SMITH, JR.

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PISTON TEMPERATURE MEASUREMENT

AND

PISTON DESIGN INVESTIGATION
ON A C.F.R. ENGINE

By

Professor G. W. Swift
Secretary of the
Massachusetts Institute of Technology,
Cambridge, Massachusetts. and
Lt. Com. N.O. Wittmann (USN)

Dear Professor Lt. Com. J.H. Smith, Jr. (USN)

We submit herewith, a thesis entitled "Piston
Submitted in Partial Fulfillment of the
Temperature Requirements for the Degree of
Investigation
on a C.F.R. Engine". MASTER OF SCIENCE

This thesis is submitted from the partial fulfillment of
the requirements of the
Massachusetts Institute of Technology
in
Mechanical Engineering June 1946

Thesis
W68

PISTON TEMPERATURE MEASUREMENT

AND

PISTON DESIGN INVESTIGATION

ON A C.V.E. ENGINE

By

Lt. Com. M.O. Wittmann (USN)

and

Lt. Com. J.H. Smith, Jr. (USN)

Submitted in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

from the

Massachusetts Institute of Technology

June 1948

ACKNOWLEDGMENT Cambridge, Massachusetts

June 1, 1946

The investigation reported in this thesis was conducted at the
Professor G. W. Swett's Laboratory, Massachusetts
Secretary of the Faculty,
Massachusetts Institute of Technology, March 1, 1946
Cambridge, Massachusetts.
to June 1, 1946.

Dear Professor Swett:

Acknowledgment of, and appreciation for, assistance

We submit herewith, a thesis entitled "Piston
in this thesis is given to the following sources:
Temperature Measurement and Piston Design Investigation
Professor W. L. Leary (M.I.T. Staff)
on a C.F.R. Engine".

Pitt and Whitney Aircraft, East Hartford, Conn.

This thesis is submitted in partial fulfillment of
Mr. J. C. Liragood (M.I.T. Staff)
the requirements for the degree of Master of Science in
Mr. R. G. Liragood
Aeronautical Engineering.

The mechanical and assistance of the Clock Laboratory.

Any opinions or statements Respectfully submitted, [Signature]

to be seen.

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RECEIVED

Massachusetts Institute of Technology

June 1, 1940

Professor C. V. Swett
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Professor Swett:

We submit herewith, a thesis entitled "Plasma
Temperature Measurement and Plasma Density Investigation
on a C.F.R. Engine".
This thesis is submitted in partial fulfillment of
the requirements for the degree of Master of Science in
Aeronautical Engineering.

PREFACE

ACKNOWLEDGMENT

The purposes of this investigation were twofold:

1. To construct a satisfactory arrangement for the measurement of piston crown temperature in a
 2. To determine the effect of piston crown design on piston temperature, with and without a forced
- The investigation reported in this thesis was conducted in the Sloan Automotive Laboratory, Massachusetts Institute of Technology, over the period March 1, 1946 to June 1, 1946.

Acknowledgment of, and appreciation for, assistance in this thesis is given to the following sources:

Professor W. A. Leary (M.I.T. Staff)

Pratt and Whitney Aircraft, East Hartford, Conn.

Mr. J. C. Livengood (M.I.T. Staff)

Mr. E. Gagger

The mechanics and assistants of the Sloan Laboratory.

Any opinions or statements contained herein represent the private views of the authors, and are not to be construed as official or in any sense reflecting those of the Navy and the naval service.

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Pratt and Whitney Aircraft, East Hartford, Conn.

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terior 1. To construct a satisfactory arrangement for the measurement of piston crown temperature in a C. F. R. Engine.

2. To determine the effect of piston crown design on piston temperature, with and without a forced system of cooling on the inside of the piston.

The subject was chosen for its particular interest to the authors in view of the considerable amount of piston "scouring" in present day engines of high speed and power. So much time has been spent on cylinder head design and so relatively little on interior piston design that it was thought advisable to attempt to find some of the trends occurring with changes in the design of the piston crown interior, and to note the effect of changes in some engine operating variables on piston crown temperatures.

T. Yamamoto and H. Nakamura ("Effect of Changes in Design and Operating Conditions on Cooling" M.I.T., 1935) attempted to measure piston temperatures on a C.F.R. engine and note the change of piston temperature with changes in crown thickness but were not highly successful due to

PREFACE

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The investigation was conducted at the University of California at Berkeley, California, during the summer of 1927.

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TABLE OF CONTENTS

| | <u>PAGE</u> |
|--------------------------------------|-------------|
| Introduction..... | 1 |
| Equipment..... | 2 |
| Procedure..... | 5 |
| Results and Discussion..... | 6 |
| Conclusions and Recommendations..... | 9 |

Appendix A

Pictures and drawings of engine and component parts. Figures 1-3.

Appendix B

Tables and Curve Sheets. Tables I, II, III, and Figures 4-16.

TABLE OF CONTENTS

| | |
|---|--------------------------------------|
| 1 | Introduction..... |
| 2 | Equipment..... |
| 3 | Procedure..... |
| 4 | Results and Discussion..... |
| 5 | Conclusions and Recommendations..... |
| | Appendix A |

References and Bibliography of sources are contained

in Appendix B.

Appendix C

Tables and Figures are contained in Appendix D.

Page 1 of 1

**PISTON TEMPERATURE MEASUREMENT
AND
PISTON DESIGN INVESTIGATION
ON A C.F.R. ENGINE**

By

Lt. Com. W. O. Wittmann (USN)

and

Lt. Com. J. H. Smith, Jr. (USN)

April - May 1946

PISTON TEMPERATURE MEASUREMENT

AND

PISTON RING INVESTIGATION

ON A C.I.E. ENGINE

BY

Mr. G. M. H. O. W. (1932)

and

Mr. G. M. H. O. W. (1932)

SUMMARY

A method of measuring piston temperature on a C.F.R. engine under operating conditions was carried through with the following results noted:

1. The method of piston temperature measurements proved very satisfactory.
2. Finning on the inside of the piston crown causes the piston to run hotter than with no finning.
3. A stream of oil under pressure applied to the under side of the piston crown lowers the piston temperature considerably, and is much more effective on a piston with deep fins on the inside of the crown than on one with no fins.
4. Piston temperatures tend to increase with an increase of engine speed.
5. Piston temperatures tend to increase with an increase of water jacket temperature.
6. Piston temperatures are highest as the fuel air ratio approaches that of best power, and drop off rapidly as the mixture is made leaner or richer than this value.
7. Inlet temperature has little effect on piston temperature.
8. Indications on one run tended to show that "blow by", caused by damaged piston rings, caused piston temperatures to be higher until rings were "worn in", indicating that a portion of the heat transfer from the piston goes to the cylinder walls via the rings.

Summary

A method of measuring piston temperature on a C.I.E. engine under operating conditions was carried through with the following results noted:

1. The method of piston temperature measurements proved very satisfactory.
2. Flaring on the inside of the piston crown causes the piston to run hotter than with no flaring.
3. A stream of oil under pressure applied to the under side of the piston crown lowers the piston temperature considerably, and is much more effective on a piston with deep flares on the inside of the crown than on one with no flares.
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8. Indications on one run tended to show that "blow by", caused by damaged piston rings, caused piston temperatures to be higher until rings were "worn in", indicating that a portion of the heat transfer from the piston goes to the cylinder walls at this time.

There is a considerable amount of investigation to be done in this field and it provides an excellent opportunity for future students to study other phases of this subject. The working system has already been constructed, they need only investigate.)

All tests were made in the Sloan Automotive Laboratory of the Massachusetts Institute of Technology by Lt. Com. N. O. Wittmann, USN, and Lt. Com. J. H. Smith, Jr., USN, under the direction of Prof. W. A. Leary of the school staff.

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PISTON TEMPERATURE MEASUREMENT AND PISTON DESIGN INVESTIGATION ON A C.F.R. ENGINE.

INTRODUCTION

Although there have been investigations made on piston temperatures, there has been little successful work along these lines attempted in this laboratory. This project has been a necessarily hastened attempt to get some satisfactory results from the measurement of piston temperature in a standard C.F.R. engine under operating conditions.

Briefly, the objects of this project were:

1. To set up a satisfactory system of measuring piston temperatures in a C.F.R. engine under operating conditions.
2. To measure the piston head temperature of three different types of pistons and note how their designs affected cooling.
3. To determine the cooling effect of a stream of oil on the lower side of the crown of each piston.
4. To determine the effect on piston temperature of changes in some of the engine operating variables.

All tests were made in the Sloan Automotive Laboratory of the Massachusetts Institute of Technology by Lt. Com. M. O. Wittmann, USN, and Lt. Com. J. H. Smith, Jr., USN, under the direction of Prof. W. A. Leary of the school staff.

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Massachusetts Institute of Technology by Mr. Com. R. O. Wittmann, VSM, and

Mr. Com. J. H. Smith, Jr., VSM, under the direction of Prof. W. A. Lewis

of the school staff.

EQUIPMENT

A standard C.F.R. single cylinder, water cooled, variable compression ratio engine of 3.25 inch bore and 4.5 inch stroke was used. (Figures 1 and 2.)

The fuel air inlet system consisted of a puff tank and a vaporizing tank, the temperature of which was controlled by any desired combination of steam or cold water. The air supply came directly from the atmosphere through a measuring orifice. The pressure differential across the orifice was measured with a standard manometer, enabling the air flow to be computed exactly at all engine speeds and conditions. The fuel was metered through a calibrated rotometer which allowed any desired fuel air ratio to be set and held constant.

The exhaust system led through a puff tank around which cold water circulated. The exhaust pressure remained essentially constant at atmospheric pressure.

The spark was controlled by a breaker mechanism coupled directly to the crankshaft in order to hold a constant spark advance.

The cylinder jacket was water cooled and the temperature of the jacket could be maintained as desired by proper admittance of cold water or steam.

The power generated by the engine was absorbed by a dynamometer of the conventional cradle type. The speed could be accurately controlled by means of a variable field coil, tachometer, and stroboscopes operating on a 60 cycle frequency.

The engine oil temperature could be varied by the proper regulation of steam and cold water to the oil heat exchanger.

The three pistons used were essentially standard C.F.R. pistons with variations in design of the inside of the crown. All the pistons had the

EXPERIMENT

A standard G.T.E. single cylinder, water cooled, variable compression
rotary engine of 3.52 inch bore and 1.5 inch stroke was used. (Figures 1
and 2.)

The fuel air inlet system consisted of a fuel tank and a vaporizing
tank, the temperature of which was controlled by any desired combination
of steam or cold water. The air supply came directly from the atmosphere
through a measuring orifice. The pressure differential across the orifice
was measured with a standard manometer, enabling the air flow to be com-
puted exactly at all engine speeds and conditions. The fuel was metered
through a calibrated rotameter which allowed any desired fuel air ratio
to be set and held constant.

The exhaust system led through a fuel tank around which cold water
circulated. The exhaust pressure remained essentially constant at atmos-
pheric pressure.

The spark was controlled by a breaker mechanism coupled directly to
the crankshaft in order to hold a constant spark advance.
The cylinder jacket was water cooled and the temperature of the jacket
could be maintained as desired by proper admittance of cold water or steam.

The power generated by the engine was absorbed by a dynamometer of
the conventional electric type. The speed could be accurately controlled by
means of a variable field coil, rheostat, and thermostat operating on a
cooling liquid.

The engine was driven by a motor of 1000 watts capacity, which was
connected to the engine through a belt and pulley system. The motor was
driven by a 220 volt, 60 cycle, alternating current supply.

same crown thickness and the same ring arrangement.

The first piston (termed the "plain piston") was a standard cast C.F.R. piston with no machining on the inside (Figures 3 and 4).

The second piston (termed the "ribbed piston") was a special casting with a grilled ribbing on the inside of the crown (Figure 5).

The third piston (termed the "finned piston") was another special casting with the deepest possible fins cast on the inside of the crown (Figures 6 and 7).

The iron constantan thermocouples were installed at a distance of $1/32$ inch from the top of the piston and in the same relative position from the center of the piston, $3/8$ inch from the center, laterally. The iron and constantan leads were brought down inside the piston to iron and constantan buttons on the lower edge of the piston skirt. These leads were held in place by small wire loops through drilled "V" holes in the piston wall. The thermocouples were installed in drilled holes approximately $1/32$ inch in diameter, and were held in place with dental cement. The iron and constantan buttons in the edge of the piston skirt were installed in micarta blocks which were shrunk fit into drilled holes in the piston skirt. The entire system, except the actual faces of the contact points, was given several coatings of glyptol (Figures 3, 5 and 6).

The take off switch was mounted on a bracket and plate which was attached to the side of the crankcase after removal of one of the crankcase side plates. Elongated holes in the plate allowed for up and down adjustment to get proper contact of switch points with the contact points on the piston skirt.

The switches were constructed from magneto breaker points that were modified to give desired results. One switch required the addition of a

same crown thickness and the same ring arrangement.

The first piston (termed the "plain piston") was a standard cast

C.V.R. piston with no machining on the inside (Figures 3 and 4).

The second piston (termed the "ribbed piston") was a special cast-

ing with a drilled ribbing on the inside of the crown (Figure 5).

The third piston (termed the "flamed piston") was another special

casting with the deepest possible fins cast on the inside of the crown

(Figures 6 and 7).

The iron constant thermocouples were installed at a distance of

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leads were held in place by small wire loops through drilled "V" holes

in the piston wall. The thermocouples were installed in drilled holes

approximately 1/32 inch in diameter, and were held in place with dental

cement. The iron and constant buttons in the edge of the piston skirt

were installed in alumina blocks which were shrunk fit into drilled holes

in the piston skirt. The entire system, except the actual faces of the

contact points, was given several coatings of epoxy (Figures 3, 5 and 6).

The take off switch was mounted on a bracket and plate which was at-

tached to the side of the crankcase after removal of one of the crankcase

side plates. Elongated holes in the plate allowed for up and down adjust-

ment to the proper location of switch points with the contact points on the

take off switch.

The take off switch was mounted on a bracket and plate which was at-

tached to the side of the crankcase after removal of one of the crankcase

constantan button to which a constantan lead wire was directly soldered. The other switch had an iron button attached to the spring, from which an iron wire was led. Both switches were insulated from each other and the bracket by bakelite. The whole assembly was covered with several coatings of glyptol (Figure 8). The switches could be adjusted laterally and vertically by set screws to match the piston skirt contacts and to contact simultaneously.

The iron and constantan leads were covered with plastic tubing and glyptol, to prevent entrance of moisture. They were led out through the switch plate to a direct reading Leeds and Northrup type potentiometer. The potentiometer was equipped with a special sensitive type of galvanometer with the following characteristics:

| | |
|-------------|-----------|
| Resistance | 17 ohms |
| Period | 5 seconds |
| Sensitivity | 0.66 A/MM |

The potentiometer was located far enough from the engine to be free of all vibrations.

The oil stream for use on the under side of the piston was taken directly from the electrically driven engine oil pump, through the contact bracket plate, and into a nozzle formed from a piece of copper tubing. The oil was supplied at a rate of 17 lbs. per minute.

constant button to which a constant lead wire was directly soldered. The other switch had an iron button attached to the spring, from which an iron wire ran. Both switches were insulated from each other and the bracket by bakelite. The whole assembly was covered with several coatings of glycol (Figure 5). The switches could be adjusted laterally and vertically by set screws to match the piston skirt contacts and to contact simultaneously.

The iron and constant leads were covered with plastic tubing and glycol, to prevent entrance of moisture. They were fed out through the switch plate to a direct reading lead and recording type potentiometer. The potentiometer was equipped with a special sensitive type of galvanometer with the following characteristics:

| | |
|-------------|----------------|
| Resolution | 15 ohms |
| Period | 2 seconds |
| Sensitivity | 0.05 μ W/V |

The potentiometer was located far enough from the engine to be free of all vibrations.

The oil stream for use on the under side of the piston was taken directly from the electrically driven engine oil pump, through the non-act bracket plate, and into a nozzle formed from a piece of copper tubing. The oil was supplied at a rate of 15 lbs. per minute.

PROCEDURE

All runs were made by setting the engine up at the desired running condition, loosening the take off switch bracket cap screws, raising the contact points until contact was evidenced on the potentiometer and then setting the contacts up approximately .02 inches further. It was found that this setting gave the most consistent results.

For each of the three pistons, the following runs were made:

1. Variation of water jacket temperature (90°F , 150°F , 210°F) for each of three different engine speeds (800, 1000 and 1200 rpms).
2. Same runs as above, but with a continuous stream of oil on the under side of the piston crown.
3. For the grilled piston, the following additional runs were made:

(a) Variation of fuel air ratio.

(b) Variation of fuel air inlet temperature.

Unless otherwise noted, the engine operating variables were kept at the following values:

| | | |
|---------------------------|-------|-------------------------|
| Inlet temperature | T_1 | 150°F |
| Water jacket temperature | T_w | 150°F |
| Crankcase oil temperature | T_o | 90°F |
| Engine oil pressure | P_o | 50 \#/in.^2 |
| Engine fuel pressure | P_f | 10.7 \#/in.^2 |
| Fuel air ratio | F | .08 |

PROCEDURE

All runs were made by setting the engine up at the desired running condition, loosening the take off switch bracket cap screws, raising the contact points until contact was evidenced on the potentiometer and then setting the contacts up approximately .05 inches further. It was found that this setting gave the most consistent results.

For each of the three pistons, the following runs were made:

1. Variation of water jacket temperature (90°F, 120°F, 210°F) for each of three different engine speeds (800, 1000 and 1200 rpm).
2. Same runs as above, but with a continuous stream of oil on the under side of the piston crown.
3. For the drilled piston, the following additional runs were

made:

(a) Variation of fuel air ratio.

(b) Variation of fuel air inlet temperature.

Unless otherwise noted, the engine operating variables were kept

at the following values:

| | | |
|--------------------------|----------------|-------------|
| Inlet temperature | T ₁ | 120°F |
| Water jacket temperature | T ₂ | 120°F |
| Exhaust gas temperature | T ₃ | 200°F |
| Inlet air pressure | P ₁ | 29.4 in. Hg |
| Exhaust gas pressure | P ₂ | 10.7 in. Hg |
| Engine speed | N | 1000 |

RESULTS AND DISCUSSION

A tabulation of the results obtained for this project is given in Tables I, II and III.

This arrangement for the measurement of piston temperatures seemed to be entirely satisfactory. No part of the system gave mechanical trouble and once the arrangement was set up, no particular difficulty in measuring the temperature was encountered. All runs were checked as many times as possible and in all cases the results were in excellent agreement.

Contrary to what had been anticipated, the plain piston ran cooler than the ribbed piston, and the latter cooler than the finned piston. In Fig. 9 the effect of changes in engine speed on piston temperature can be seen. There is a general rise in piston temperature when engine speed is increased, with all other engine operating conditions held constant. It can be seen that the finned piston ran the hottest. Just why this is so is not definitely known, although it is suspected that the deep fins retard air circulation and oil splashing on the under side of the piston crown and thus more heat is retained by the crown, causing higher temperatures. Some of the difference in temperature may be due to the additional amount of piston material above the piston pin bosses in the plain piston, causing more heat to be carried away through this path, and consequently giving better cooling of the piston. However, the fact that the finned piston runs hotter than the ribbed piston of similar design and weight tends to discount this theory.

The forced system of carrying heat away proves very effective in all cases, and particularly so in the case of the finned piston. The final

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in the plain piston, causing more heat to be carried away through the

pins, and consequently giving more cooling of the piston. However,

the fact that the flared piston ran hotter than the ribbed piston is

still a question and may be due to some other factor.

The following table gives a summary of the results obtained in all

runs.

result is not as encouraging as was to be expected since the finned piston ran much hotter before the oil stream was applied. However, there are indications that some combination of deep finning plus forced heat removal may have possibilities in lowering the piston crown temperature and preventing scouring of pistons at present day high engine speeds and power.

Fig. 10 and Fig. 11 are repetitions of Fig. 9 at higher water jacket temperature and show the same trends.

Figs. 12, 13 and 14 show the variation of piston temperature with change in water jacket temperature at 800, 1000 and 1200 rpms respectively. Again, the finned piston runs hot and the plain piston cooler, until a forced oil stream is added and then the temperature trends are reversed. In general, the piston temperatures increase with increase in water jacket temperature, but the rate of increase is lowered as piston temperature is lowered.

Fig. 15 shows the effect of changes in fuel air ratio and inlet temperature on piston temperature. At very lean fuel air ratios, piston temperatures are low, but build up rapidly with an increase in fuel air ratio until approximately best power fuel air ratio is reached, at which point the temperatures reach their maximum, then drop off rapidly with further enrichening of fuel air ratio.

Changes of inlet temperature within the range of this setup gave little change in piston temperature.

Fig. 16 was an accidental occurrence that might well be investigated by future students. When the engine was started with new rings on the piston, "blow by" was indicated by a considerable amount of smoke coming

result is not as encouraging as was to be expected since the limited piston run much better before the oil stream was applied. However, there are indications that some combination of deep timing plus forced heat removal may have possibilities in lowering the piston crown temperature and preventing excessive of piston at present day high engine speeds and power. Figs. 10 and 11 are repetitions of Fig. 9 at higher water jacket temperatures and show the same trends.

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Fig. 16 is an additional example that might well be illustrated

by other examples. This is the engine run at 1000 rpm with

oil temperature 100°F. The oil was changed at 1000 rpm and

through the crankcase breather pipe. Also, piston temperatures were considerably higher than on all previous runs starting under the same conditions but with no apparent "blow by". As the time after starting increased, the smoke gradually decreased and piston temperatures lowered, until after about six hours of running, the temperatures were constant and agreed with previous runs; and the smoke from the breather ceased. It is thought that these new rings may have been scratched or were in some other way irregular, allowing "blow by" until they were properly "worn in". The "blow by" prevented the usual amount of heat transfer between the piston, piston ring, and cylinder walls, and caused higher piston temperatures until the point was reached where the rings were "worn in", no "blow by" occurred, and normal heat transfer to the cylinder walls took place.

It is suggested that further investigation along these lines could profitably be made by future students. The actual set-up is now completed and another group would not have to spend a considerable portion of their limited time in repeating what has already been accomplished, and could devote all of their time to more thorough and complete investigation of actual piston designs. It is further suggested that the plain piston should be machined on the under side of the crown to the same dimensions as the other two pistons and that perhaps another piston with slightly shorter fins could be investigated. Other subjects for investigation would be the use of a stream of compressed air on the under side of the piston crown, and a check on the effects of "blow by" on piston temperatures.

through the crankcase pressure pipe. Also, piston temperatures were considerably higher than on all previous runs starting under the same conditions but with no apparent "blow by". At the time after starting increased, the smoke gradually decreased and piston temperatures lowered until after about six hours of running, the temperatures were constant and agreed with previous runs; and the smoke from the pressure crankcase. It is thought that these new rings may have been seatbed or were in some other way irregular, allowing "blow by" until they were properly "worn in". The "blow by" prevented the usual amount of heat transfer between the piston, piston ring, and cylinder walls, and caused higher piston temperatures until the point was reached where the rings were "worn in", no "blow by" occurred, and normal heat transfer to the cylinder walls took place.

It is suggested that further investigation along these lines could profitably be made by future attempts. The actual set-up is now completed and another group would not have to spend a considerable portion of their limited time in repeating what has already been accomplished, and could devote all of their time to more thorough and complete investigation of actual piston design. It is further suggested that the plain piston should be retained on the motor side of the group to the same dimensions as the other two pistons and that perhaps another piston with slightly different lines could be investigated. Under a light load for investigation would be the use of a mixture of compressed air on the motor side of the piston, and a check on the effect of "blow by" on piston

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were arrived at as the result of this investigation:

1. The method of piston temperature measurement used proved very satisfactory.
2. Finning on the inside of the piston crown causes the piston to run hotter than with no finning.
3. A stream of oil under pressure applied to the under side of the piston crown lowers the piston temperature considerably, and is much more effective on a piston with deep fins on the inside of the crown than on one with no fins.
4. Piston temperatures tend to increase with an increase of engine speed.
5. Piston temperatures tend to increase with an increase of water jacket temperature.
6. Piston temperatures are highest as the fuel air ratio approaches that of best power, and drop off rapidly as the mixture is made leaner or richer than this value.
7. Inlet temperature has little effect on piston temperature.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were arrived at as the result of this investigation:

1. The method of piston temperature measurement used proved very satisfactory.
2. Flaming on the inside of the piston crown causes the piston to run hotter than with no flaming.
3. A stream of oil under pressure applied to the under side of the piston crown lowers the piston temperature considerably, and is much more effective on a piston with deep flange on the inside of the crown than on one with no flange.
4. Piston temperature tends to increase with an increase of engine speed.
5. Piston temperature tends to increase with an increase of water jacket temperature.
6. Piston temperature is highest at the fuel air

and the temperature that is best power, and the the piston is not a factor of this value.

It is suggested that the following be done:

8. Indications on one run tended to show that "blow by", caused by damaged piston rings caused piston temperatures to be higher until rings were "worn in", indicating that a portion of the heat transfer from the piston goes to the cylinder walls via the rings.

The following recommendations are made as suggestions for future study:

1. More intensive investigation of the three piston designs used for this project, with the "plain piston" machined under the crown to the wall dimensions of the other pistons.
2. Investigation of pistons of other designs, particularly with fin length between that of the "ribbed piston" and that of the finned piston.
3. Investigation of the use of compressed air on the under side of the piston crown to produce forced cooling.
4. Investigation of the effects of "blow by" on piston temperature.
5. Investigation of the heat flow through the piston crown by putting a number of thermocouples in the crown and upper ring land.

8. Indications on one run tended to show that "blow by", caused by damaged piston rings caused piston temperatures to be higher until rings were "worn in", indicating that a portion of the heat transfer from the piston goes to the cylinder walls via the rings.

The following recommendations are made as suggestions for future study:

1. More intensive investigation of the three piston designs used for this project, with the "plain piston" machined under the crown to the wall dimensions of the other pistons.
2. Investigation of pistons of other designs, particularly with fin length between that of the "ribbed piston" and that of the lined piston.
3. Investigation of the use of compressed air on the under side of the piston crown to produce forced cooling.
4. Investigation of the effects of "blow by" on piston temperatures.
5. Investigation of the effects of "blow by" on the heat transfer from the piston to the cylinder walls.

APPENDIX A

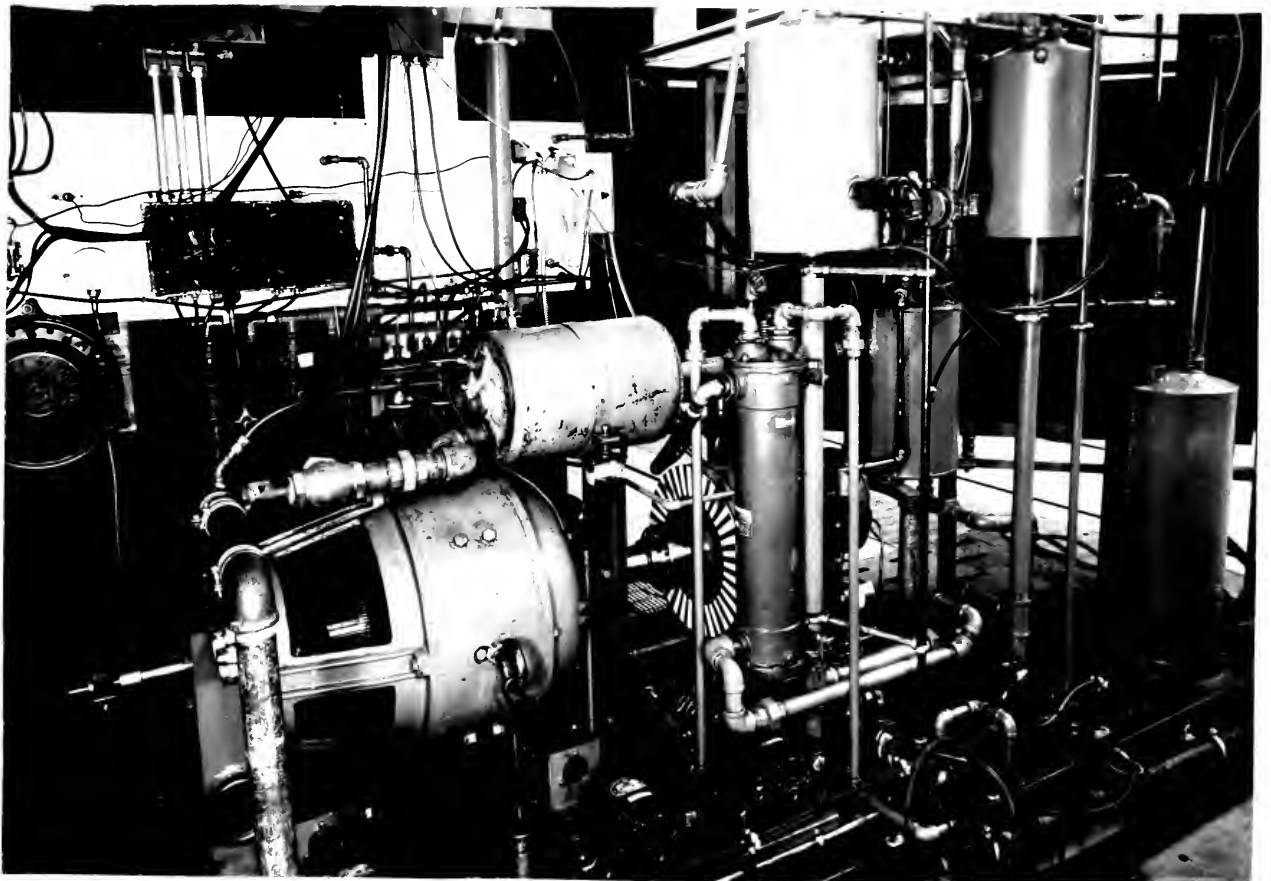
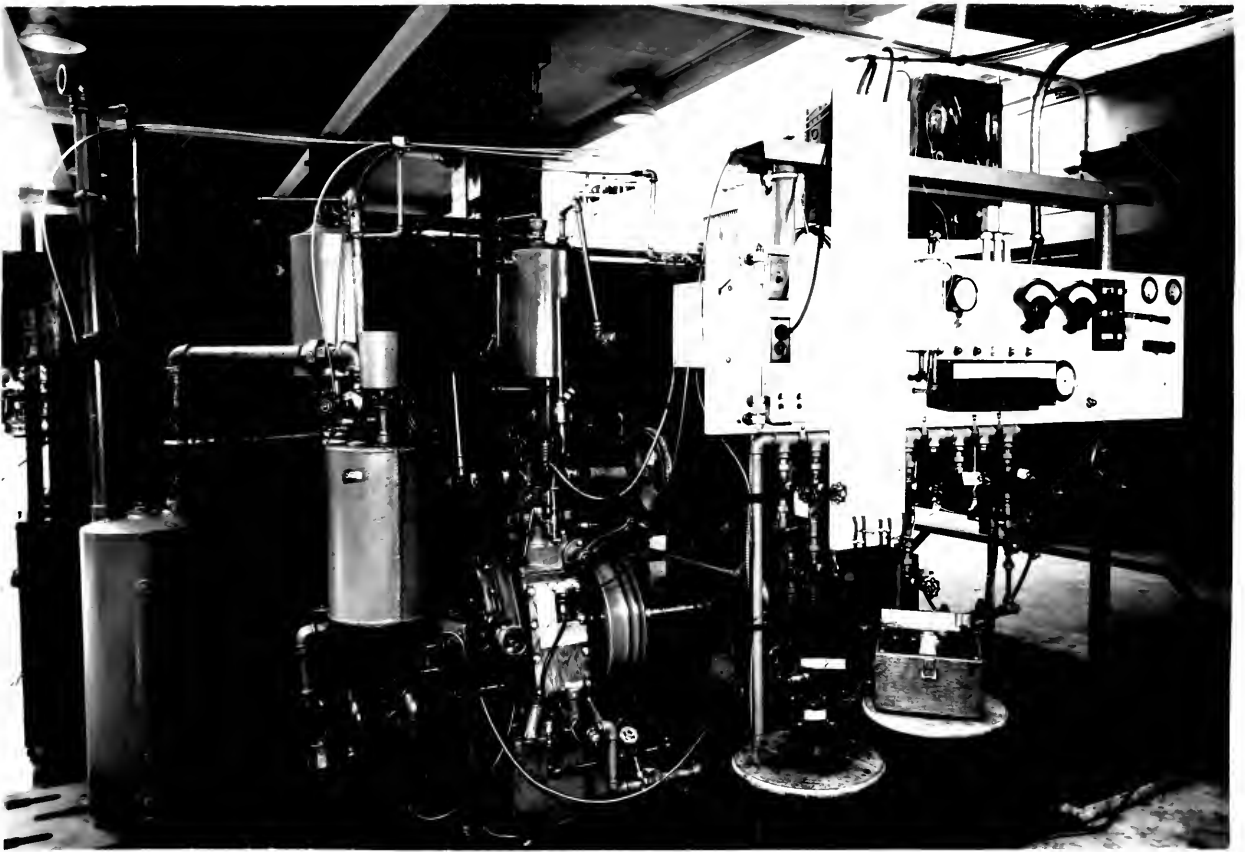


FIG. 1
ENGINE LAYOUT

Fig. 1
ENGINE LAYOUT

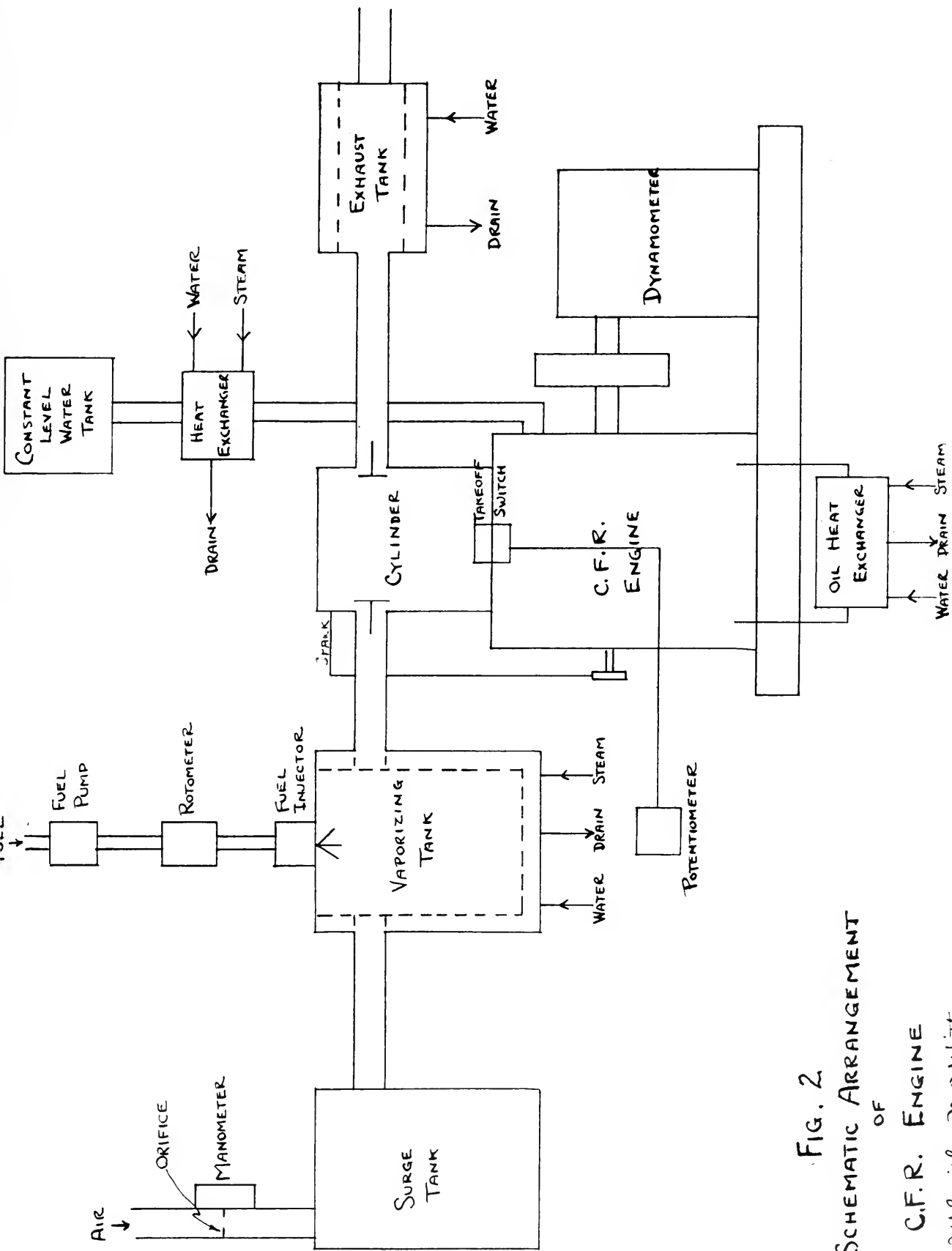


FIG. 2
SCHEMATIC ARRANGEMENT
OF

C.F.R. ENGINE

W. Smith - N.O. Wittmann



FIG. 3
PLAIN PISTON

Plain Protein
Fig. 3

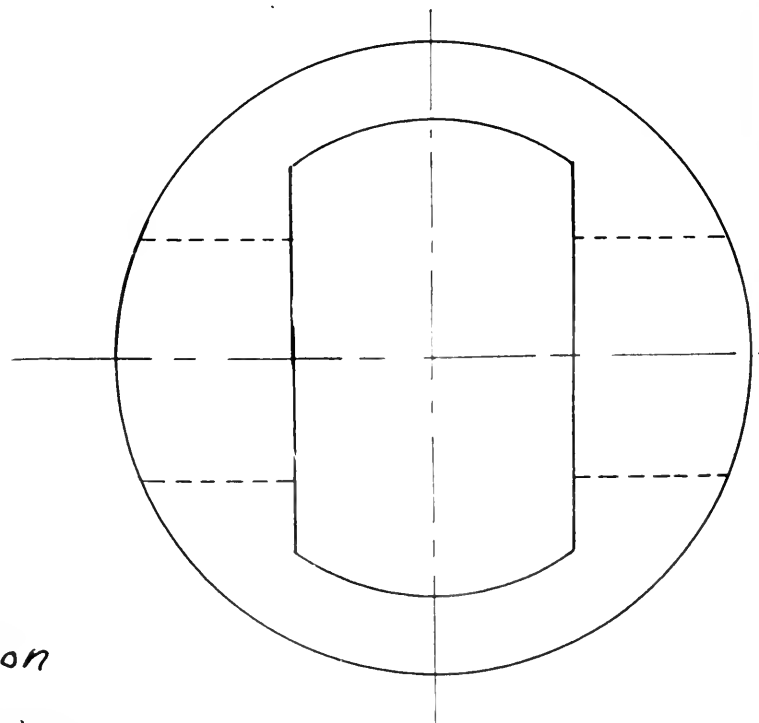
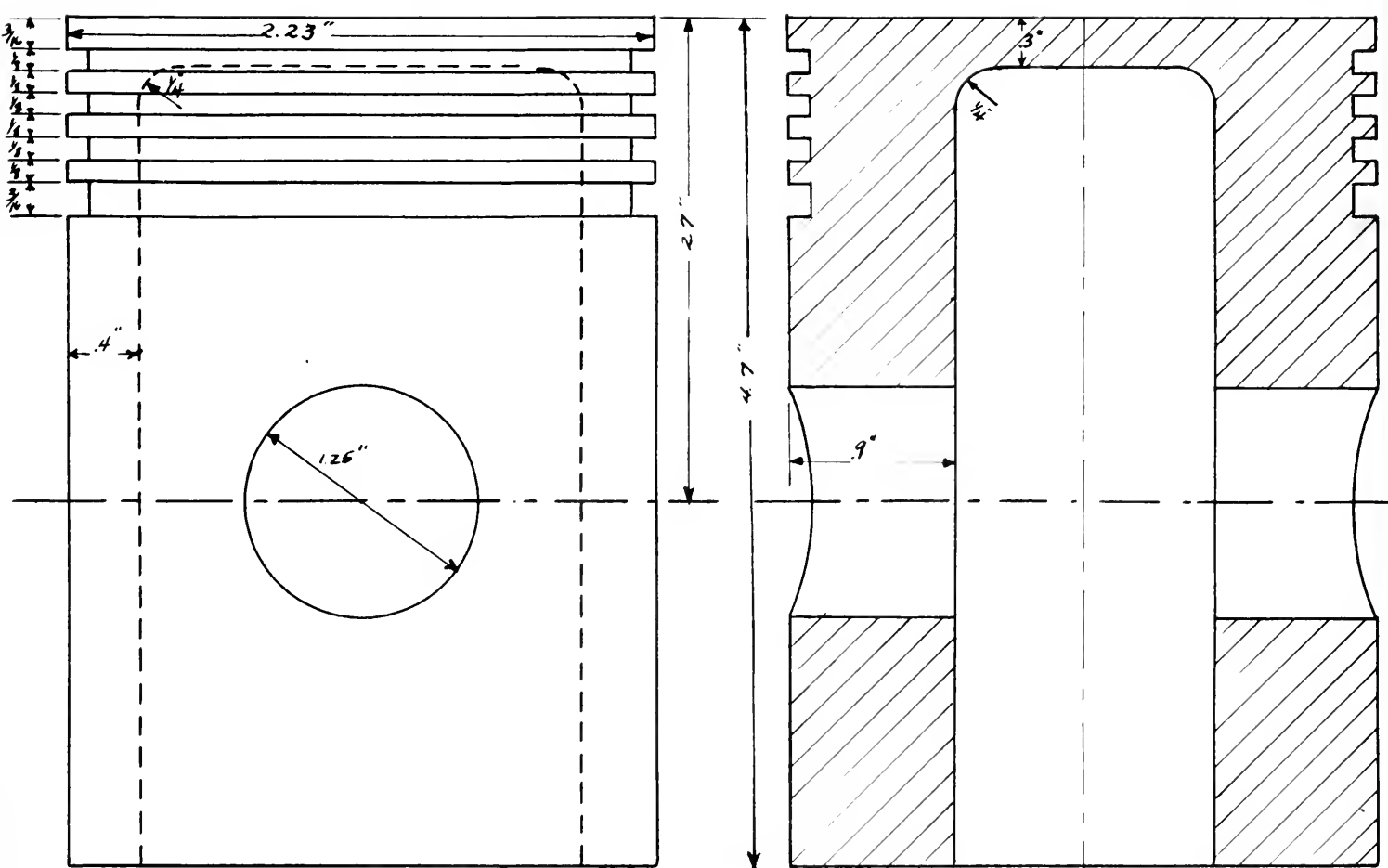


Fig. 4

C.F.R. Engine Piston

Lt. Com J. I. Smith, Jr. & Lt. Com N. O. Wittmann





FIG. 5
RIBBED PISTON



Fig. 2
Niger Plateau



FIG. 6
FINNED PISTON



Fig. 6
Finned Piston

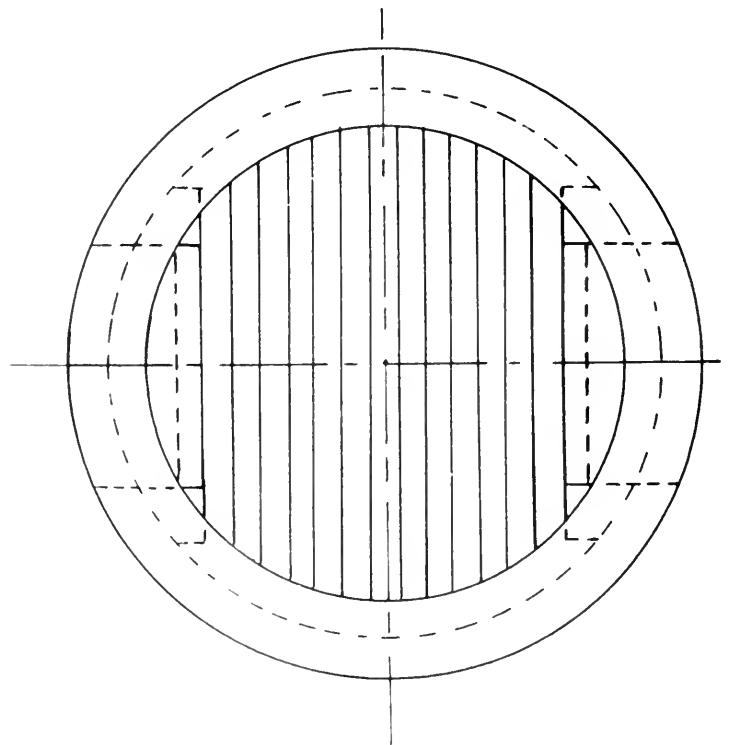
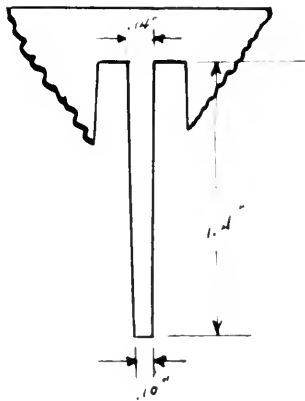
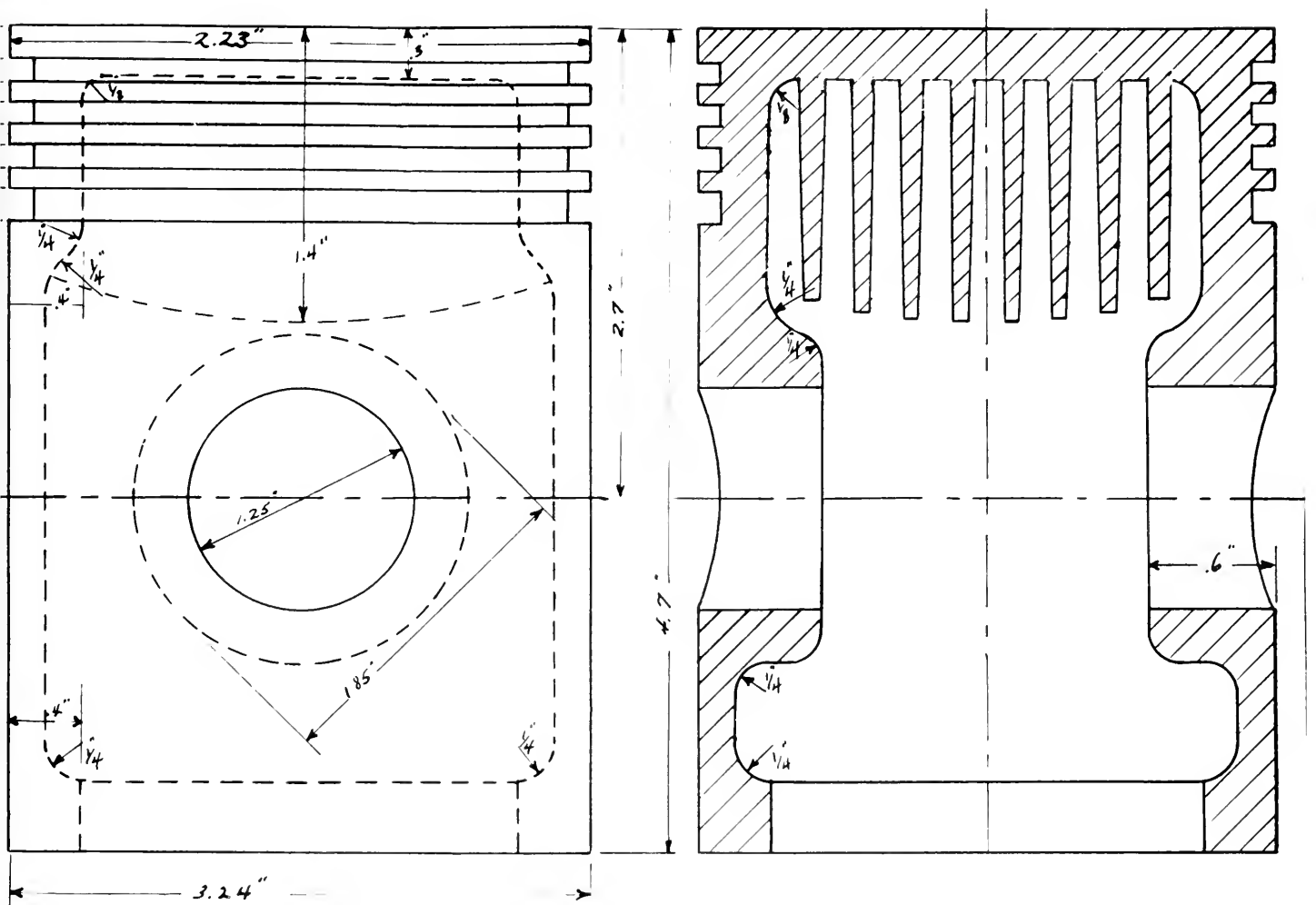
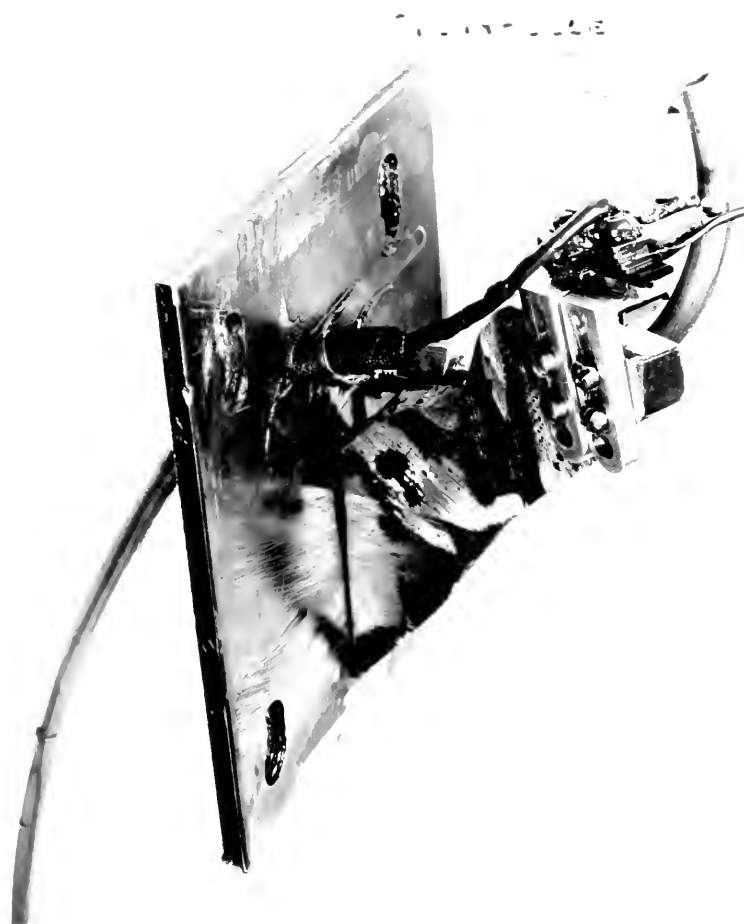


FIG. 7
C.F.R. Engine Piston
With Deep Fins



THE END OF THE LINE

Take off Switch Bracket

Fig. 8

| dev | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
|------|------|------|------|------|------|------|------|------|------|-------|
| 100 | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
| 200 | 200 | 400 | 600 | 800 | 1000 | 1200 | 1400 | 1600 | 1800 | 2000 |
| 300 | 300 | 600 | 900 | 1200 | 1500 | 1800 | 2100 | 2400 | 2700 | 3000 |
| 400 | 400 | 800 | 1200 | 1600 | 2000 | 2400 | 2800 | 3200 | 3600 | 4000 |
| 500 | 500 | 1000 | 1500 | 2000 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 |
| 600 | 600 | 1200 | 1800 | 2400 | 3000 | 3600 | 4200 | 4800 | 5400 | 6000 |
| 700 | 700 | 1400 | 2100 | 2800 | 3500 | 4200 | 4900 | 5600 | 6300 | 7000 |
| 800 | 800 | 1600 | 2400 | 3200 | 4000 | 4800 | 5600 | 6400 | 7200 | 8000 |
| 900 | 900 | 1800 | 2700 | 3600 | 4500 | 5400 | 6300 | 7200 | 8100 | 9000 |
| 1000 | 1000 | 2000 | 3000 | 4000 | 5000 | 6000 | 7000 | 8000 | 9000 | 10000 |

APPENDIX B

| | | | | | | | | | |
|------|------|------|------|------|------|------|------|------|-------|
| 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
| 200 | 400 | 600 | 800 | 1000 | 1200 | 1400 | 1600 | 1800 | 2000 |
| 300 | 600 | 900 | 1200 | 1500 | 1800 | 2100 | 2400 | 2700 | 3000 |
| 400 | 800 | 1200 | 1600 | 2000 | 2400 | 2800 | 3200 | 3600 | 4000 |
| 500 | 1000 | 1500 | 2000 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 |
| 600 | 1200 | 1800 | 2400 | 3000 | 3600 | 4200 | 4800 | 5400 | 6000 |
| 700 | 1400 | 2100 | 2800 | 3500 | 4200 | 4900 | 5600 | 6300 | 7000 |
| 800 | 1600 | 2400 | 3200 | 4000 | 4800 | 5600 | 6400 | 7200 | 8000 |
| 900 | 1800 | 2700 | 3600 | 4500 | 5400 | 6300 | 7200 | 8100 | 9000 |
| 1000 | 2000 | 3000 | 4000 | 5000 | 6000 | 7000 | 8000 | 9000 | 10000 |

APPENDIX B

PLAIN PISTON

| REV. PER MINUTE | T _w (°F) | RUN #1 PISTON TEMP (°F) | RUN #2 PISTON TEMP (°F) | RUN #3 PISTON TEMP (°F) | RUN #4 PISTON TEMP (°F) | | PISTON TEMP (WITH OIL) (°F) | PISTON TEMP (WITH OIL) (°F) |
|-----------------------|------------------------|----------------------------------|----------------------------------|----------------------------------|----------------------------------|--|--------------------------------------|--------------------------------------|
| 800 | 90 | 248 | 255 | 258 | 246 | | 203 | 202 |
| " | 150 | 282 | 291 | 298 | 283 | | 222 | 232 |
| " | 210 | 323 | 325 | 328 | 326 | | 245 | 260 |
| 1000 | 90 | 267 | 265 | 275 | 255 | | 218 | 220 |
| " | 150 | 298 | 302 | 295 | 297 | | 236 | 242 |
| " | 210 | 333 | 347 | 351 | 346 | | 261 | 270 |
| 1200 | 90 | 275 | 282 | 285 | 272 | | 244 | 225 |
| " | 150 | 310 | 312 | 321 | 318 | | 250 | 257 |
| " | 210 | 340 | 348 | 342 | 351 | | 261 | 270 |

RIBBED PISTON

| | | | | | | | | |
|------|-----|-----|-----|-----|--|--|-----|--|
| 800 | 90 | 275 | 257 | 256 | | | 198 | |
| " | 150 | 312 | 303 | 297 | | | 215 | |
| " | 210 | 352 | 347 | 343 | | | 234 | |
| 1000 | 90 | 286 | 265 | 267 | | | 187 | |
| " | 150 | 320 | 287 | 287 | | | 215 | |
| " | 210 | 358 | 345 | 342 | | | 226 | |
| 1200 | 90 | 299 | 277 | 282 | | | 207 | |
| " | 150 | 329 | 312 | 315 | | | 207 | |
| " | 210 | 370 | 347 | 351 | | | 235 | |

FINNED PISTON

| | | | | | | | | |
|------|-----|-----|-----|-----|--|--|-----|--|
| 800 | 90 | 308 | 288 | 270 | | | 175 | |
| " | 150 | 340 | 330 | 312 | | | 175 | |
| " | 210 | 372 | 352 | 349 | | | 175 | |
| 1000 | 90 | 318 | 312 | 310 | | | 185 | |
| " | 150 | 344 | 341 | 342 | | | 198 | |
| " | 210 | 382 | 370 | 365 | | | 202 | |
| 1200 | 90 | 328 | 330 | 318 | | | 200 | |
| " | 150 | 358 | 365 | 345 | | | 202 | |
| " | 210 | 380 | 370 | 365 | | | 195 | |

F/A = .08

T_w = 150°F

TABLE I

T₀ = 90°F

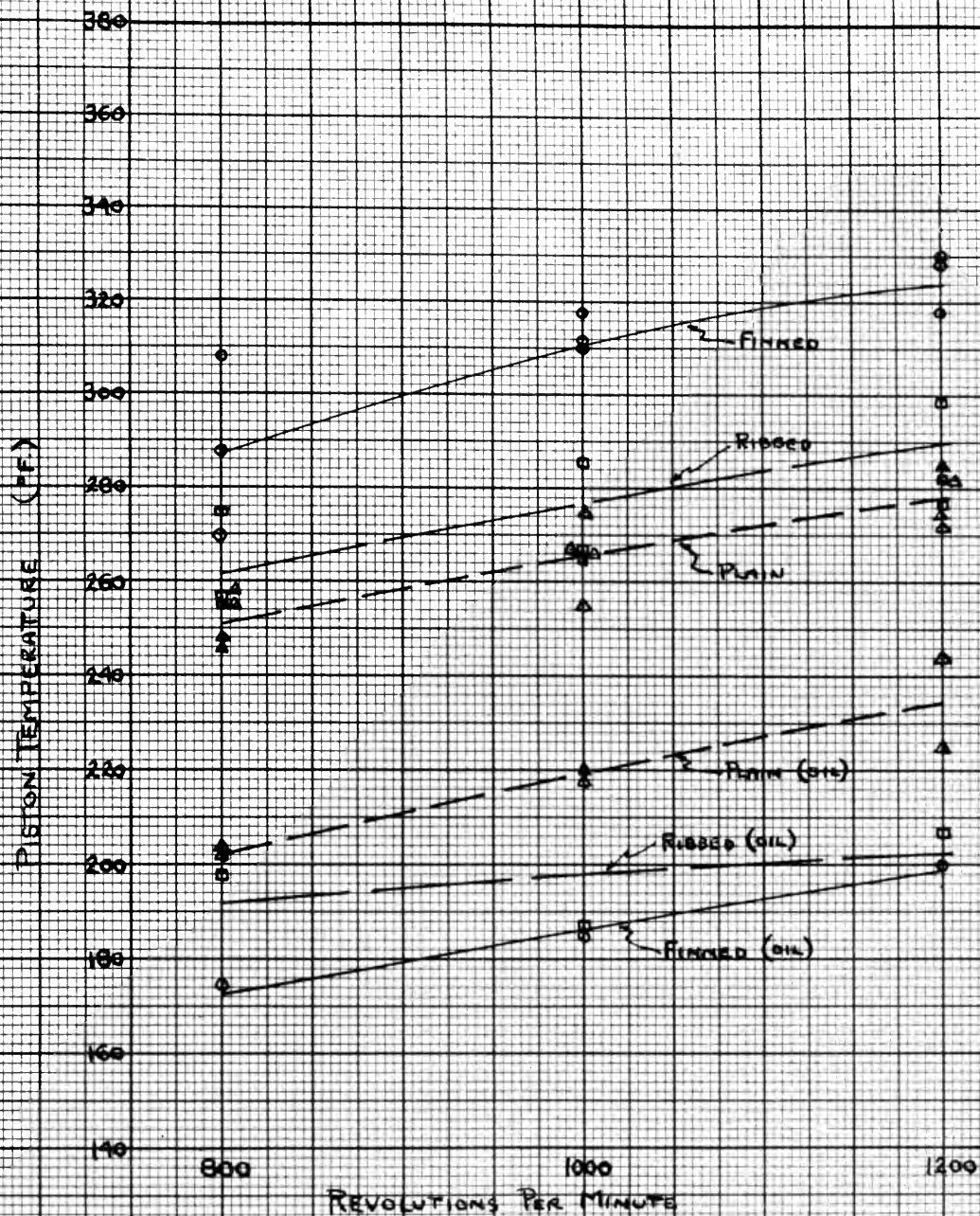
P₀ = 49 lb/in²

VARIAION OF PISTON TEMPERATURE
WITH RPM AND WATER JACKET TEMPERATURE

| FUEL AIR RATIO | PISTON TEMP | FUEL AIR RATIO | PISTON TEMP | INLET TEMP | PISTON TEMP |
|-------------------|----------------|-------------------|----------------|---------------|----------------|
| .055 | 255 | .10 | 312 | 105 | 328 |
| .06 | 278 | .11 | 298 | 120 | 328 |
| .07 | 306 | .12 | 285 | 140 | 331 |
| .08 | 325 | .13 | 275 | 160 | 332 |
| .09 | 320 | .14 | 271 | 174 | 331 |

TABLE II
VARIAION OF PISTON TEMPERATURE
WITH FUEL AIR RATIO

TABLE III
VARIAION OF PISTON TEMPERATURE
WITH INLET TEMPERATURE



$T_w = 90^\circ\text{F}$

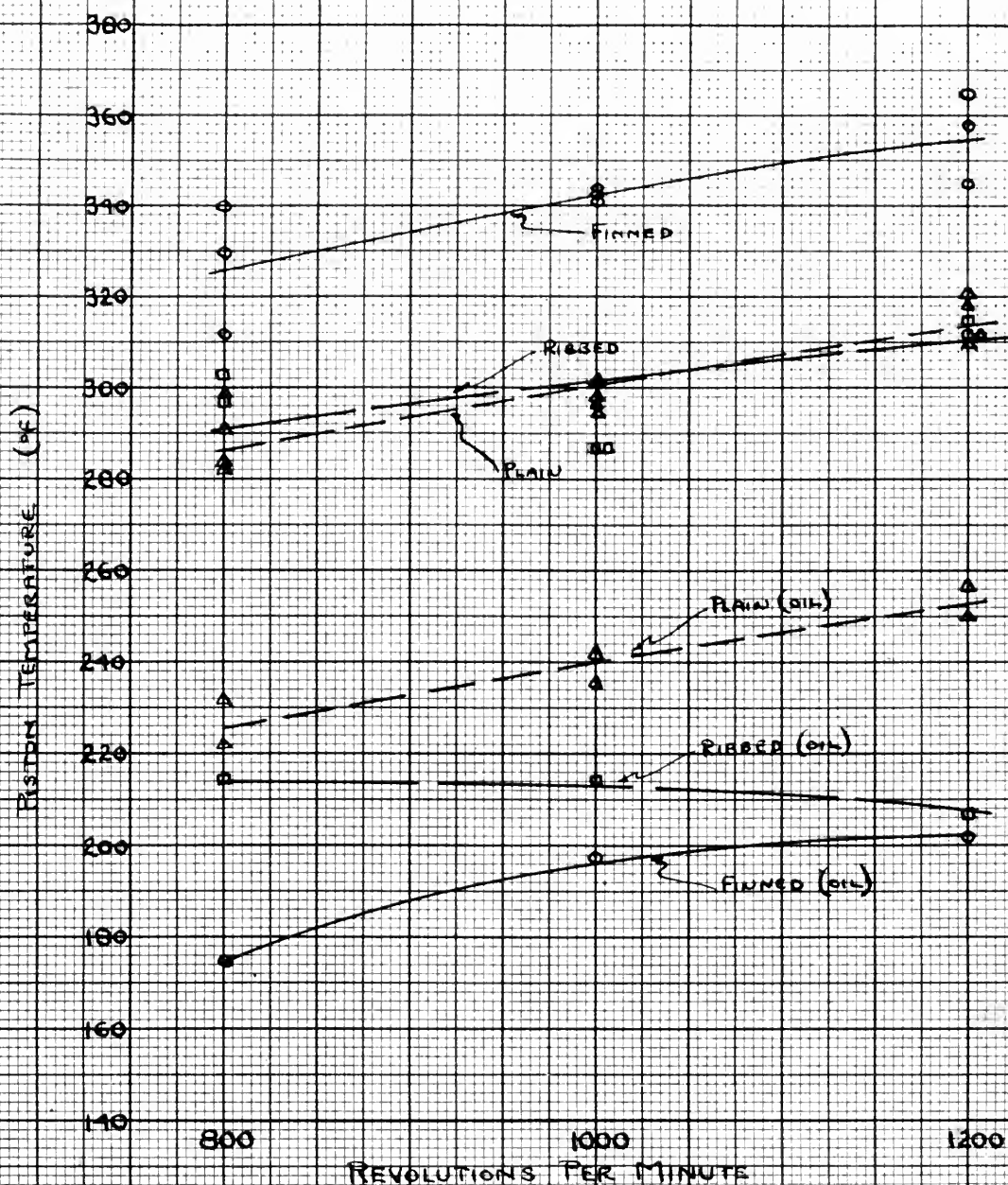
$F/A = .03$ $T_w = 90^\circ\text{F}$ $T_c = 150^\circ\text{F}$ $T_g = 90^\circ\text{F}$ $p = 50 \text{ lb/in}^2$ $P_L = 10.7 \text{ lb/in}^2$

FIG. 9

VARIATION OF PISTON TEMPERATURE
WITH RPM FOR THREE TYPES OF
PISTONS - SHOWING EFFECT OF OIL STREAM

GAS M.O.W.

4-27-40

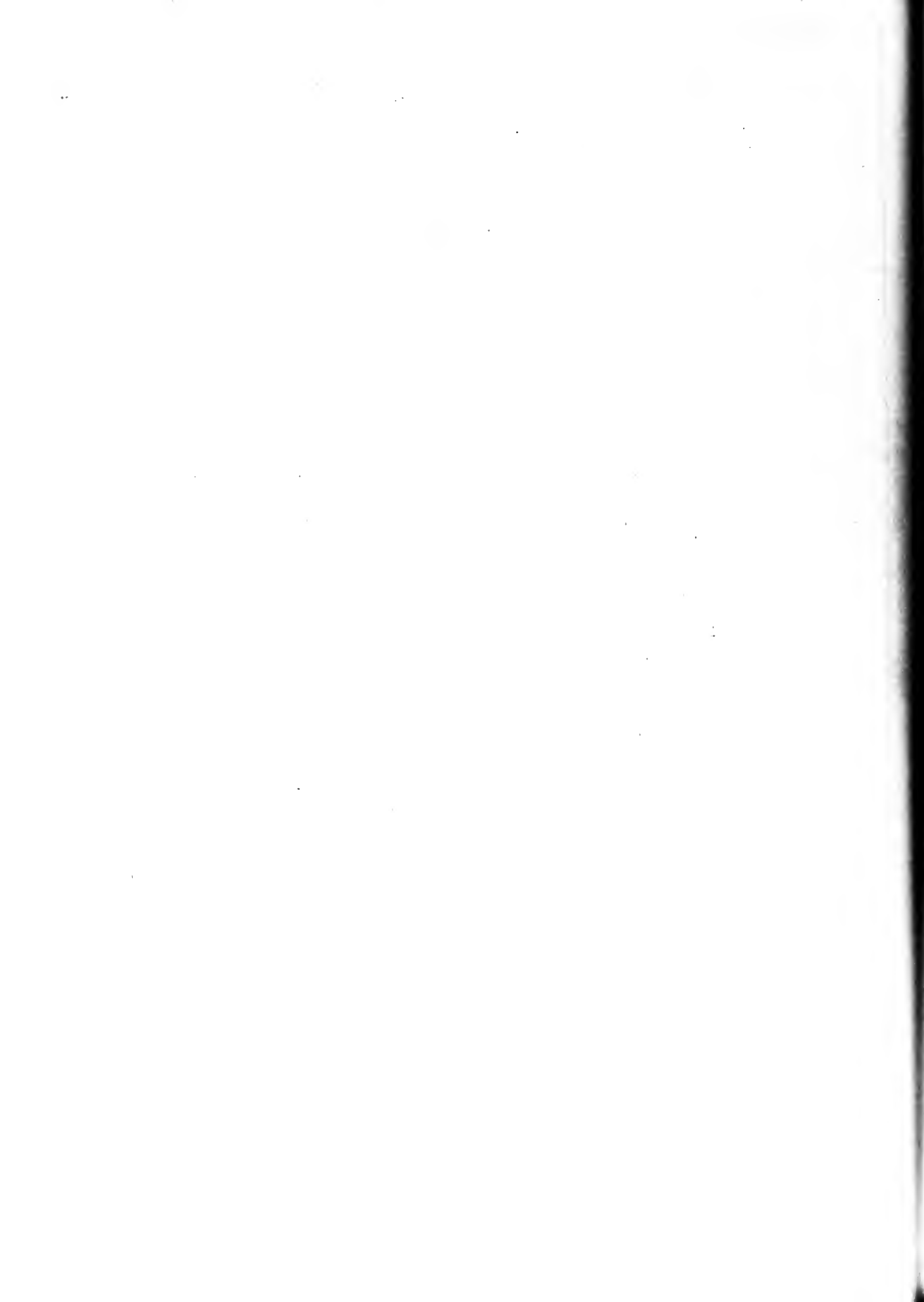


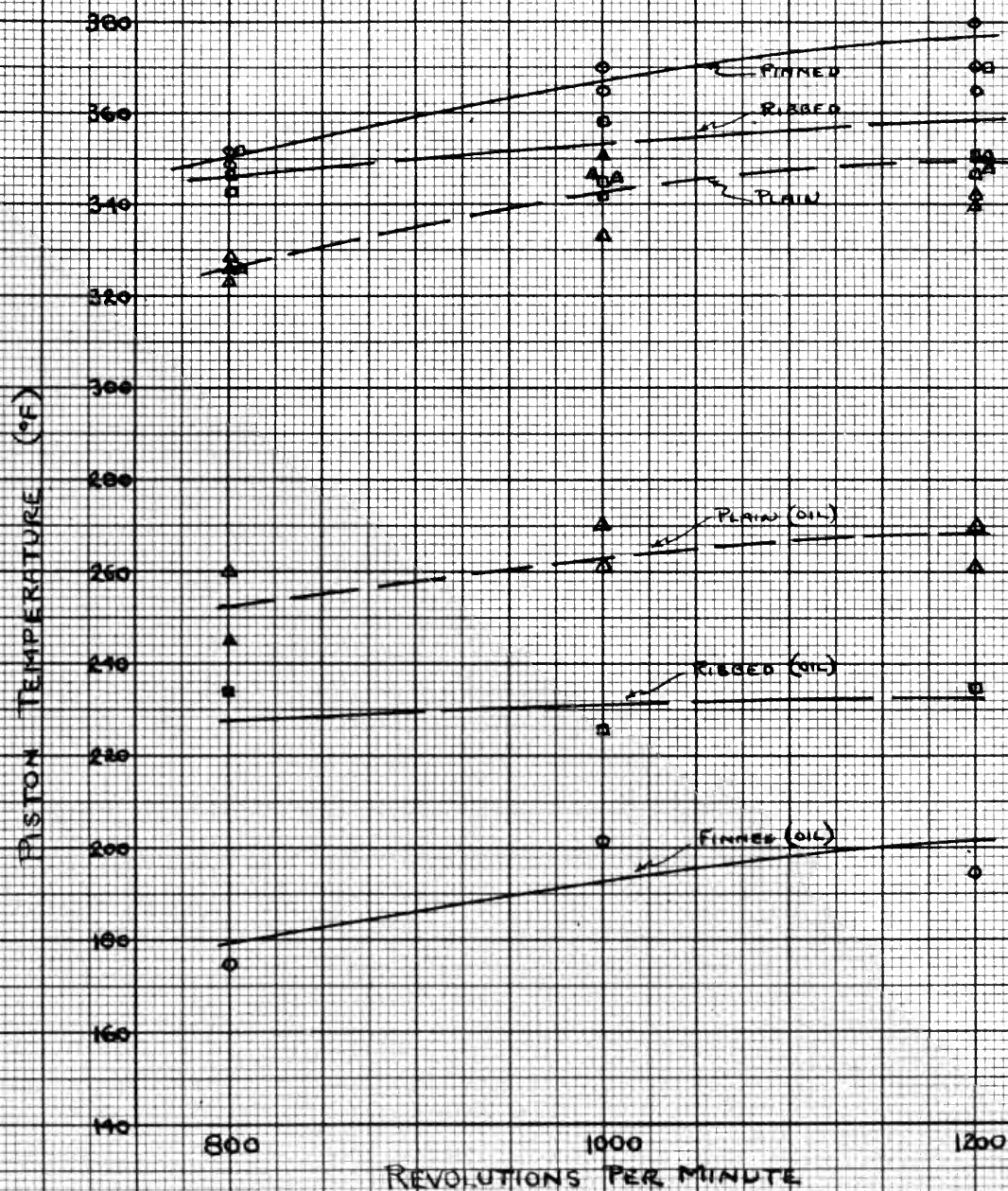
$T_w = 150^\circ\text{F}$

$P/A = .08$ $T_i = 150^\circ\text{F}$ $T_o = 90^\circ\text{F}$ $p_o = 50 \text{ lb/in}^2$ $p_c = 10.7 \text{ lb/in}^2$

FIG. 10

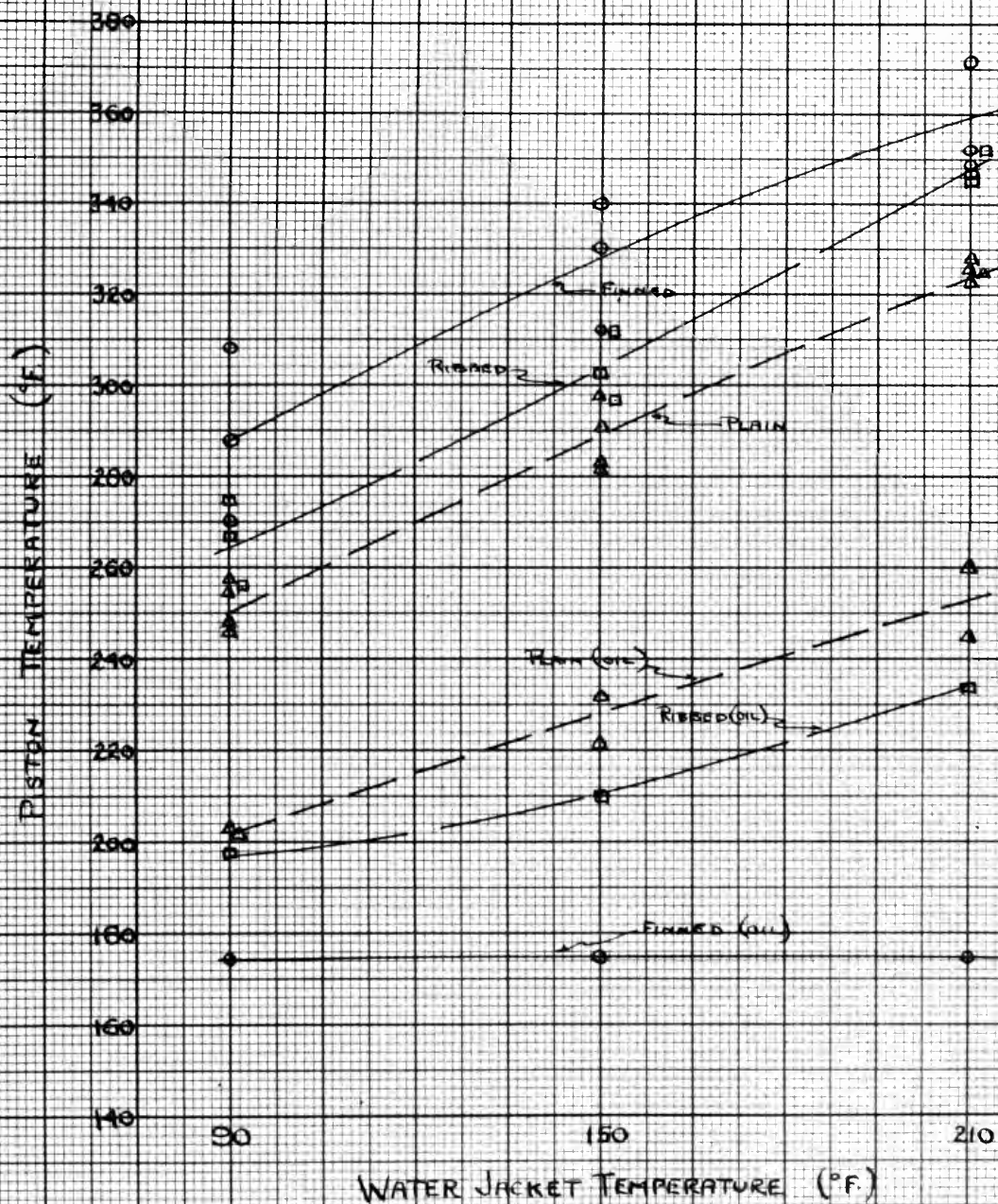
VARIATION OF PISTON TEMPERATURE
WITH RPM. FOR THREE TYPES OF
PISTONS - SHOWING EFFECT OF OIL STREAM
JAS H.O.W. 4-27-46





$T_w = 210^\circ\text{F}$
 $F/A = .08$ $T_o = 150^\circ\text{F}$ $T_s = 30^\circ\text{F}$ $p_o = 50 \text{ lb/in}^2$ $p_r = 10.7 \text{ lb/in}^2$

FIG. 11
 VARIATION OF PISTON TEMPERATURE
 WITH R.P.M. FOR THREE TYPES OF PISTONS.
 SHOWING EFFECT OF OIL STREAM
 GAS FLOW 4-27-79



RPM = 800

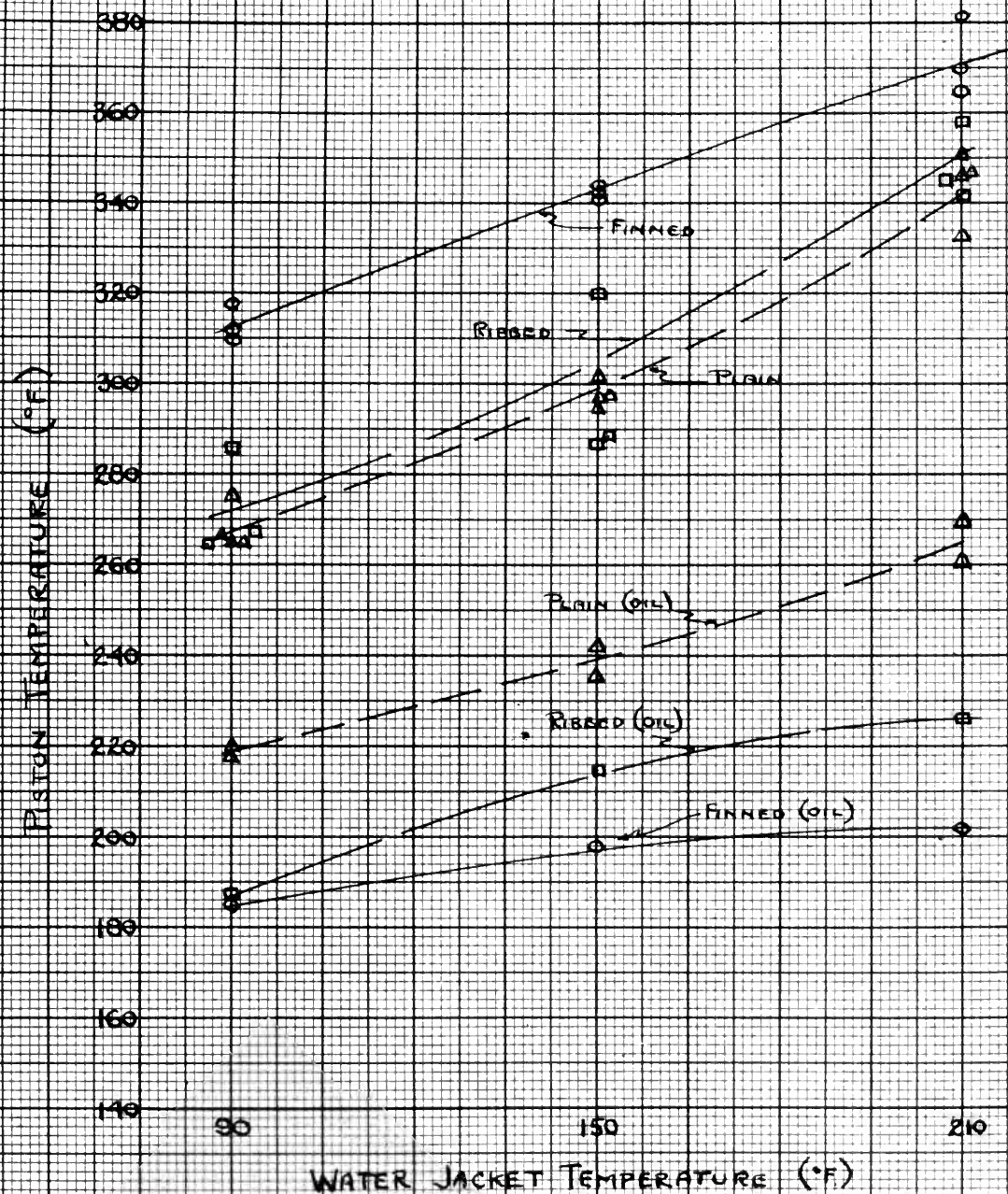
$F/A = .08$ $T_c = 150^\circ\text{F}$ $T_o = 30^\circ\text{F}$ $p_c = 50 \text{ lb/in}^2$ $p_o = 10.7 \text{ lb/in}^2$

FIG. 12

VARIATION OF PISTON TEMPERATURE
WITH WATER JACKET TEMPERATURE
FOR THREE TYPES OF PISTONS
SHOWING EFFECT OF OIL STREAM

JOS N.O.W.

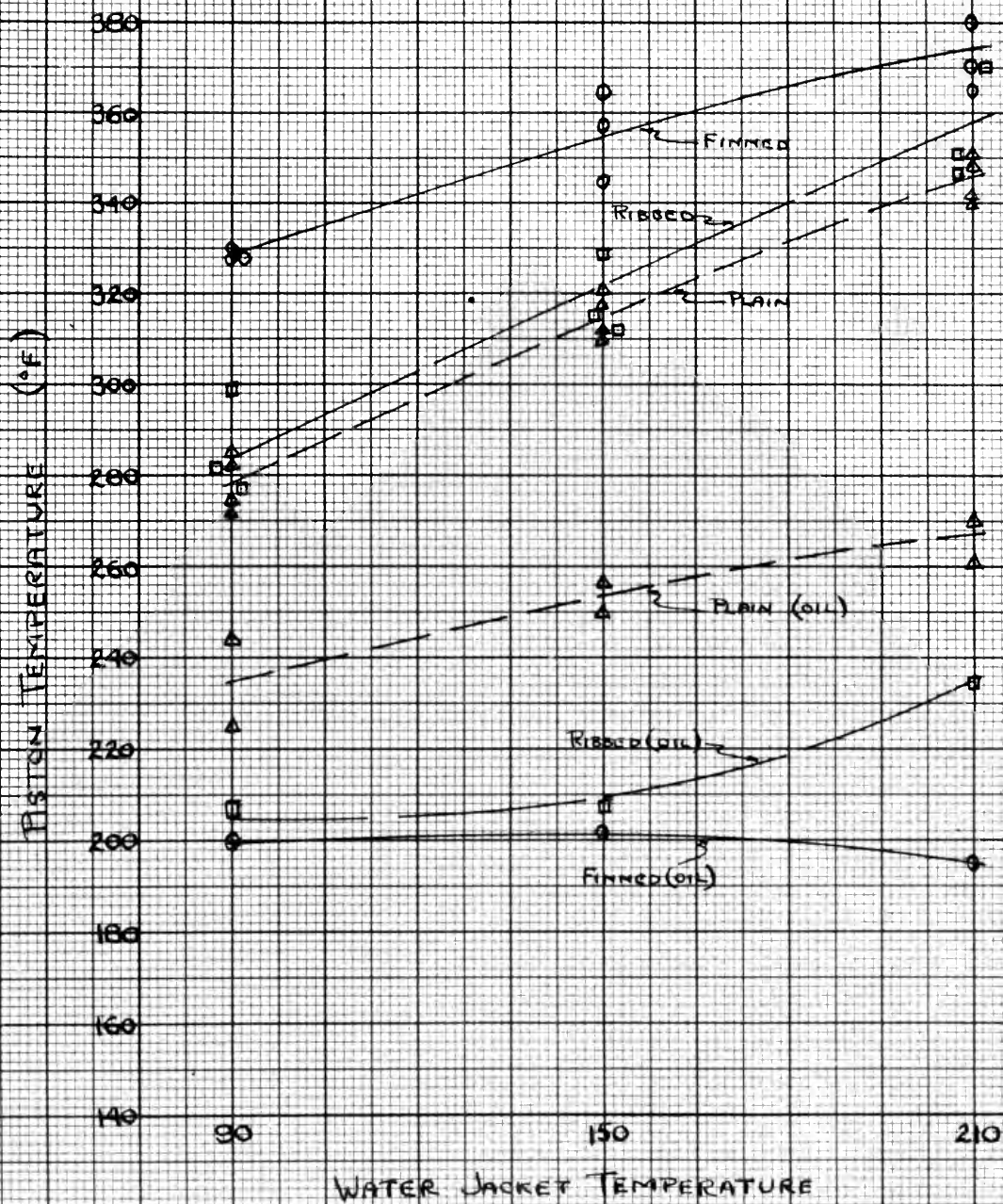
4-27-46



RPM = 1000
 $F/A = .08$ $T_c = 150^\circ\text{F}$ $T_o = 30^\circ\text{F}$ $p_o = 50 \text{ lb/in}^2$ $p_c = 10.7 \text{ lb/in}^2$

FIG. 13
 VARIATION OF PISTON TEMPERATURE
 WITH WATER JACKET TEMPERATURE
 FOR THREE TYPES OF PISTONS
 SHOWING EFFECT OF OIL STREAM
 JAS. M.O.W. 4-27-46



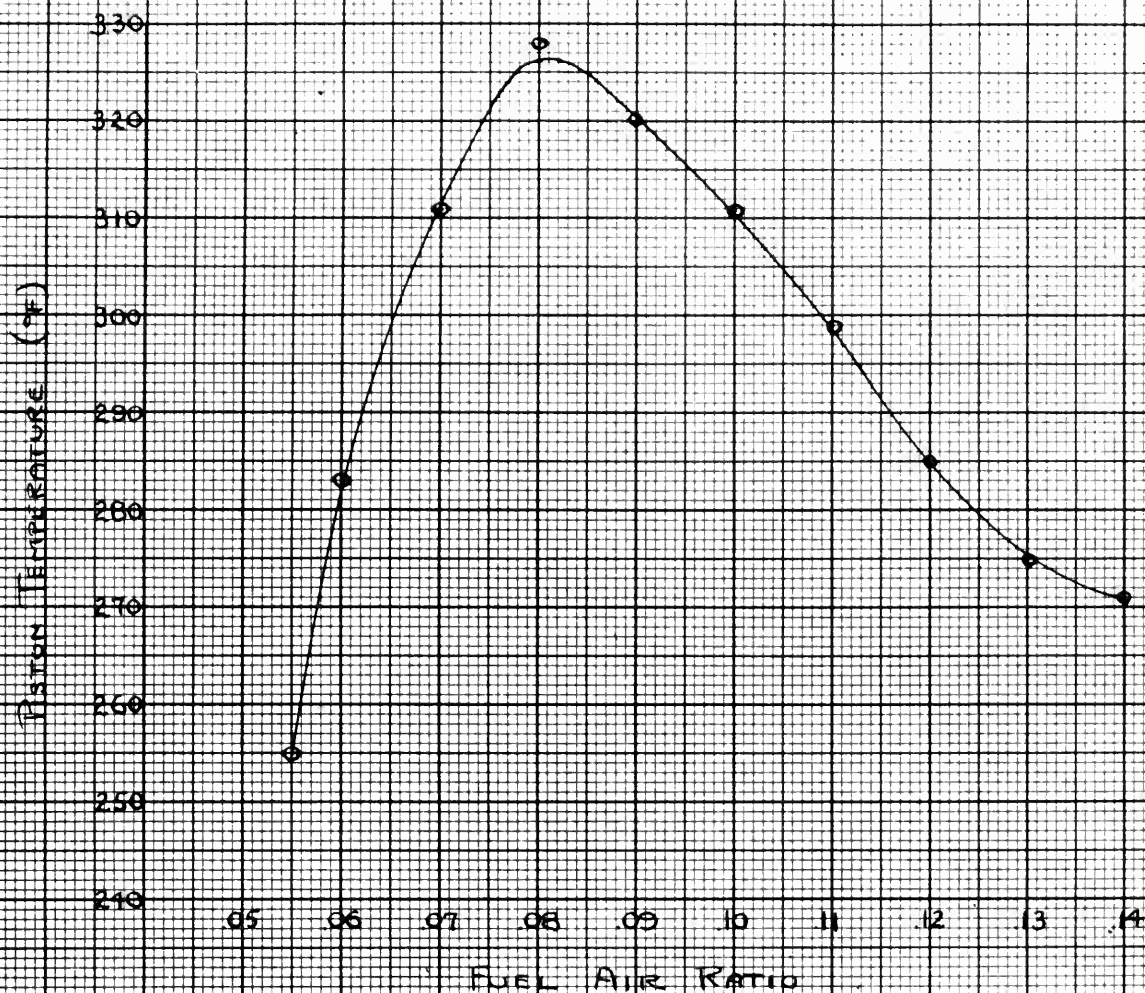


$F/A = .08$ $T_c = 150^\circ\text{F}$ $T_o = 90^\circ\text{F}$ $P_o = 50 \text{ lb/in}^2$ $P_c = 10.7 \text{ lb/in}^2$

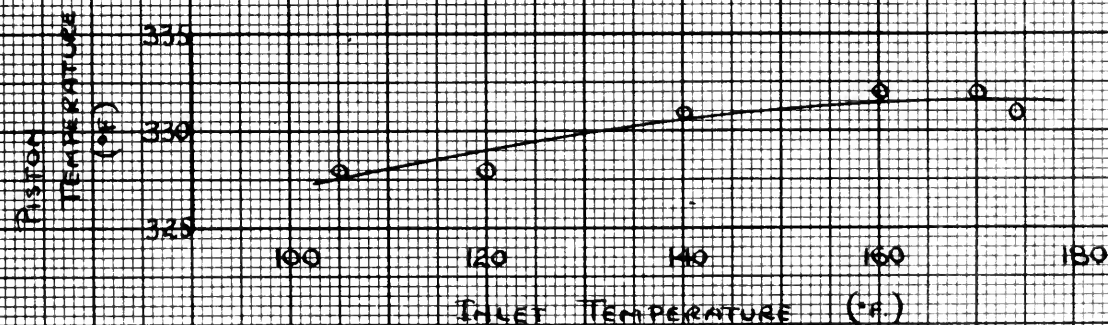
FIG 14

VARIATION OF PISTON TEMPERATURE
 WITH WATER JACKET TEMPERATURE
 FOR THREE TYPES OF PISTONS
 SHOWING EFFECT OF OIL STREAM
 JAS N.O.W. 4-27-46





$T_c = 130^\circ\text{F}$ $T_w = 150^\circ\text{F}$ $\text{RPM} = 1200$ $T_b = 90^\circ\text{F}$ $p_c = 50 \text{ lb/in}^2$ $p_b = 19.7 \text{ lb/in}^2$
 R10500 PISTON



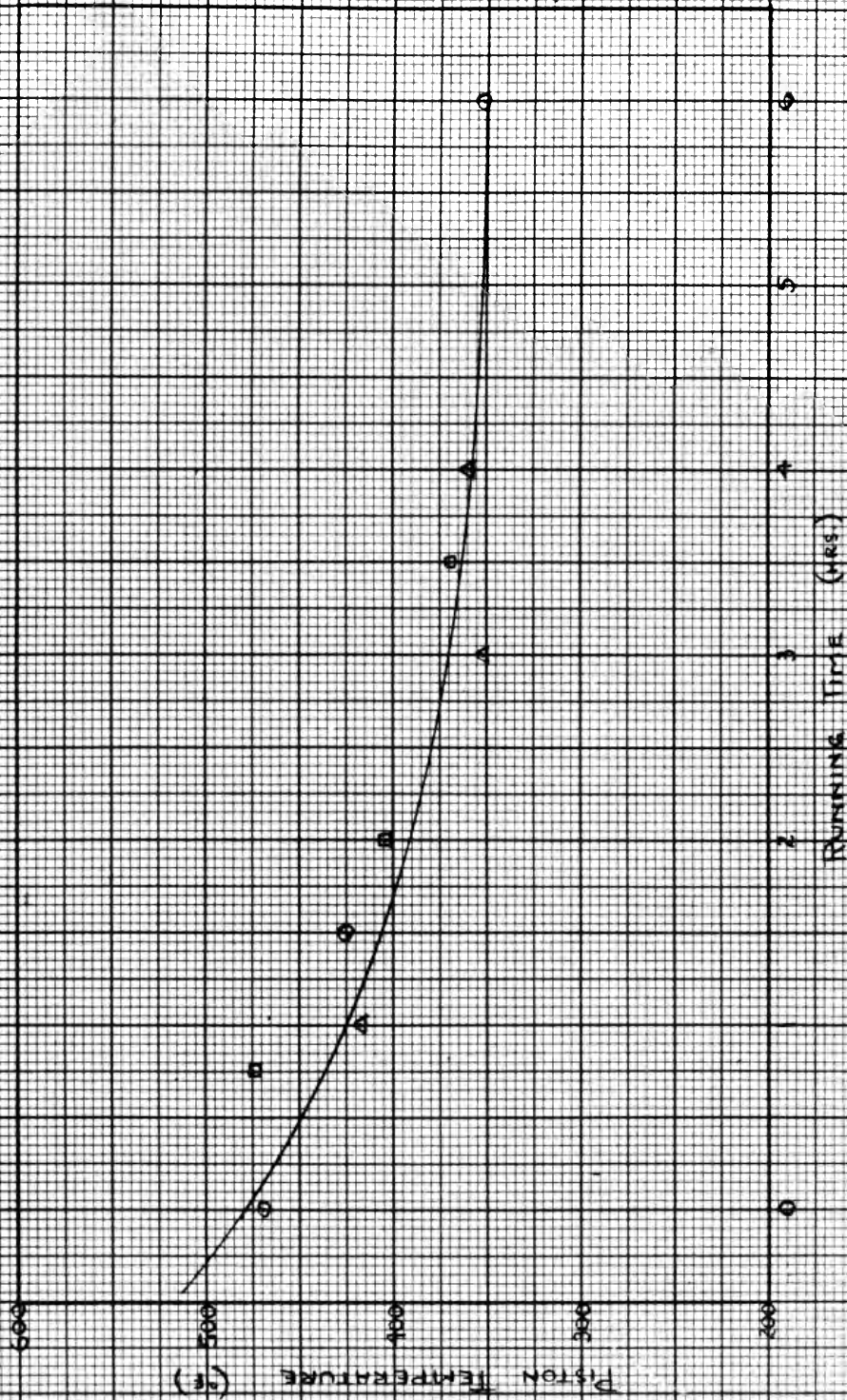
$F/A = 0.8$ $T_w = 150^\circ\text{F}$ $\text{RPM} = 1200$ $T_b = 90^\circ\text{F}$ $p_c = 50 \text{ lb/in}^2$ $p_b = 19.7 \text{ lb/in}^2$
 R10500 PISTON

FIG 15

VARIATION OF PISTON TEMPERATURE
 WITH FUEL AIR RATIO AND INLET TEMPERATURE

YOS Now

4-26-46



$T_c = 150^\circ\text{F}$
 $T_w = 150^\circ\text{F}$
 $F/A = .08$
 Finned Piston
 $RPM = 1000$
 $P_c = 50.16 \text{ (in.)}$
 $P_r = 10.716 \text{ (in.)}$

FIG 16

PISTON TEMPERATURE VARIATION WITH
 RING WEAR IN WHEN RING "BLOW BY"
 WAS IN EVIDENCE

SWS: MOW
 4-29-46

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Piston temperature
measurement and piston
design investigation on
a CFR engine.

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